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FINAL REPORT

Search for Self-Stimulation of Long-Lived Isomer Decay

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I. INTRODUCTION

The main technical objective of the Phase I research was to observe experimentally as the stimulated γ-ray emission in long-lived tellurium isotopes ^{125m}Te and ^{123m}Te, as the stimulated conversion electron emission in ^{123m}Te. And though all preparations for a number of measurements have already been completed as long as the last year, our Research Reactor has not been started not only in October, as it was planned before, but is still shut down now.

As one can note, in order to pump effectively the long-lived nuclear isomers, in our case there is not any alternative but the reactor. Really, taking into account that the maximum density of the excited states could be reached during the time of irradiation of the order of the transition lifetime, the usage of accelerators for pumping turns out to be too expensive. At the same time, one should not forget that the neutrons interact very strongly with the nuclei and, on the other hand, produce only minimal damage to the crystals. The latter is very important for the Moessbauer Effect to occur, necessary for the emitted γ-rays to be coherent. So, there is no other way to conduct successfully the experiments on the search for self-stimulation of long-lived nuclear isomers, as to wait till our Research Reactor will be started. And though after the reconstruction of Physical Protection System, which should be finished completely within a month or so, we have never been so close to it as nowadays, unfortunately, everything can happen.

As a result, we have been forced to pay our attention mainly to the supporting objectives of the Phase I research. First, an experiment, which is not based on the assumption that the stimulating and stimulated photons are time-coincident, has been planned, just as the advanced technique of the search for stimulated γ-ray emission has been developed. The idea is to compare, for the source in the form of a long filament, the number of simple pulses, corresponding to the

isomeric transition energy, counted in the axial direction with the number seen off-axis. It is interesting that, if the stimulating and stimulated photons are time-coincident, such the technique of measurements has essential advantages as well.

Secondly, for the successful search of self-stimulation in long-lived isomers ^{125m}Te and ^{123m}Te, one needs to use the Te compounds with extremely high Debye temperature. And though ZnTe crystals, having the Debye temperature as high as 295K, appear to be very useful for such the experiments, moreover, not too less effective than BeTe, there are both simple (like OsTe) and complex (for example, Mg_3TeO_6) tellurium compounds, the Debye temperature of which could be even much higher than that for BeTe. Thus, it would be very interesting to try to synthesize them as well.

And at last, some efforts have been undertaken to find any additional theoretical support for our experiments.

II. AN ADVANCED TECHNIQUE OF THE SEARCH FOR STIMULATED GAMMA-RAY EMISSION

As it has already been mentioned before [1], long-lived nuclear isomers ^{125m}Te and ^{123m}Te have the best chances in the experimental search for stimulated γ-ray emission. Moreover, if, in the case of ^{125m}Te, the measurements of single γ-ray spectra have the highest accuracy in observing the peaks corresponding to twice the isomeric transition energy, then, in the case of ^{123m}Te, it is more preferable to register the coincidence spectra.

And though we believe that the γ-ray stimulation process is really instantaneous [2] and, as a result, the stimulating and stimulated photons should be time-coincident and can be registered simultaneously by a detector as the sum peak, we are planning to perform another experiment, which is not based on the assumption that the stimulating and stimulated photons are time-coincident. The idea is for the source in the form of a long filament to compare the number of simple-energy pulses, corresponding to once the isomeric transition energy, counted in the axial direction with the number seen off-axis. In order to eliminate the factor of time it seems to be useful to collect the γ-spectra for rather short and equal intervals of time by the same detector as along the axis as off-axis alternately, simply turning the source around. For that purpose a rotating system has been developed and designed (Fig. 1), which turns the source over 90 degrees to the right just as the exposure is over. As a result, we can collect simultaneously in different buffers as far as four γ-ray spectra, two in the axial direction and two in the off-axis one. One can expect that

the stimulated photons would be detected preferably in the on-axis spectra, and, on the other hand, they are practically absent in the off-exis spectra.

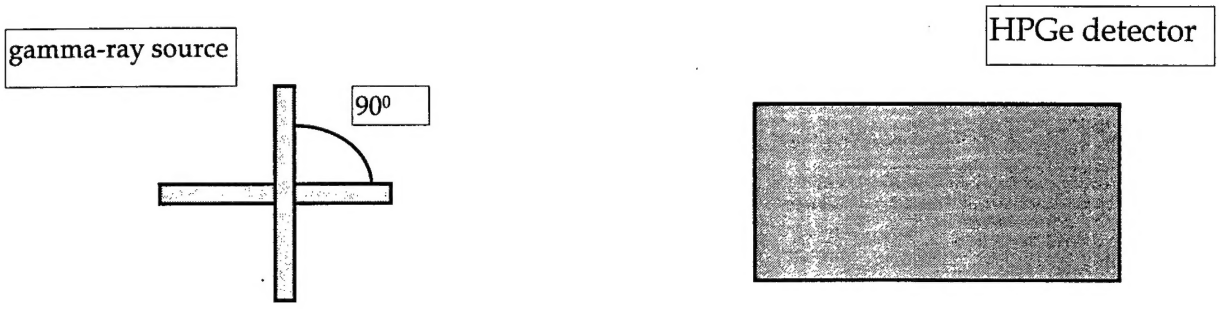

Fig. 1. Schematic representation of the experimental set-up, which rotates the gamma-ray source 90^0 to the right every time, when the exposure is over.

Furthermore, if the stimulating and stimulated photons are time-coincident yet, such the technique has some and quite essential advantages, as well. For instance, as for a pile-up problem, it is well-known that because the summing effects will depend on the square of the detector solid angle, whereas the simple peaks vary linearly, the relative effect of summing can be reduced by reducing the solid angle. So, having found the peaks corresponding to twice the transition energy, we can easily test whether they are the result of the stimulated γ-ray emission or not, by simply changing the source-detector spacing. Another way to check it is to change the source temperature. Naturally, for example, at room temperature the probability of stimulated γ-ray emission turns out to be so small that all impulses, registered in the peaks corresponding to twice the isomeric transition energy, will be exclusively chance coincidences because of the summing effect.

Alternatively, by measuring the γ-spectra according to the technique described above, one can solve the pile-up problem quite naturally. Really, in the on-axis spectra the impulses, detected in the channel corresponding to twice the isomeric transition energy, will be a result of as the stimulated γ-ray emission as the chance coincidences, whereas in the off-axis spectra practically every impulse, detected in that channel, is the accidental sum peak. Moreover, because the number of the chance coincidences in both kind of the spectra would be practically the same, it seems to be very useful that there is a possibility to extract apart and quite naturally the effect of the stimulated γ-ray emission.

III. SEARCH OF STRUCTURES AND COMPOUNDS, USEFUL FOR THE SELF-STIMULATION DETECTION IN LONG-LIVED NUCLEAR ISOMER DECAY

It is well-known that to observe the Moessbauer Effect with high-energy γ-transitions (E_γ > 80 keV) a host having the high Debye temperature, Θ_D is essential. That is why, for the search of self-stimulation in long-lived isomers ^{125m}Te (E_γ = 109.27 keV) and ^{123m}Te (E_γ = 88.5 keV), one needs to use the Te compounds with extremely high Debye temperature. One of such the structures is ZnTe crystal, the Debye temperature of which, according to the estimate got in [1], should be around 250-300K. More precise estimate can be received taking into consideration that the maximum energy of phonons in ZnTe (LO phonon) is equal to 205 cm^{-1} [3] and that corresponds to the Debye temperature Θ_D(ZnTe) = 295K. Thus, the f-factors, which define the fraction of recoilless photons, for the isomeric transitions in ^{125m}Te and ^{123m}Te at liquid nitrogen temperature (T = 78K) will be equal to 1.2% and 5.3%, respectively, almost as it has been supposed in [1]. Moreover, though we can't guarantee the ideal quality of our ZnTe crystals, since they were grown from rather small amounts of highly enriched isotopes, as a good fortune, ^{125m}Te is the well-known Moessbauer nucleus and there is a chance for the recoil-free fraction of the samples to be carefully measured.

At the same time, though Be has really very high Debye temperature (Θ_D(Be) = 1440K), BeTe compound is not the most useful for the search of self-stimulation in long-lived nuclear isomers, because of the very small atomic weight of beryllium. Really, for the case of an impurity of mass m_i, in a monatomic Debye solid characterized by m_h, experience has shown that one merely needs to replace the host Θ_D by an effective Debye temperature:

$$\Theta_D^{eff.} = \Theta_D \sqrt{\frac{m_h}{m_i}} \quad , \qquad (1)$$

So, the Debye temperature of, for instance, such compound as CrTe turns out to be equal to 406K, a bit higher, than that for BeTe (for which Θ_D(BeTe) = 390K), though the Debye temperature of chromium is much lower (Θ_D(Cr) = 630K), than the Debye temperature of beryllium. Moreover, for the compound RuTe (if only it ever exists and could be synthesized), since Θ_D(Ru) = 600K, the Debye temperature would be equal to 539K, i.e. even much higher, than in the case of BeTe.

However, the most useful could be such the compounds of Te, when a monatomic solid with rather high Debye temperature is characterized by the mass much more heavy, than the tellurium mass. There is a small group of transitional elements as W, Re, Os and Ir, the Debye temperatures of which are in the range of 400K-500K. Thus, the Debye temperature of WTe

appears to be equal to 485K and the Debye temperature of OsTe - as high as 616K. Moreover, since all that are the diatomic compounds, high-frequency optic modes are present in addition to the acoustic modes. The presence of these modes can substantially enhance the f-factor of a solid, so that the effective Debye temperature will be even higher than what one could get according to (1). For example, according to (1) the Debye temperature of BeTe is equal to 390K, whereas it used to be estimated as 440K.

So, the f-factors, which define the fraction of recoilless photons, for the isomeric transitions in ^{125m}Te and ^{123m}Te at the liquid nitrogen temperature (T = 78K) will be equal to 11.6% and 23.8% in the case of WTe and 20.1% and 34.3% in the case of OsTe, respectively. It is interesting that at the measurement temperature T→0 the f-factors reach 15.9% and 29.3%, in the case of WTe, and even 23.5% and 38.0%, in the case of OsTe, for ^{125m}Te and ^{123m}Te, respectively. Thus, one can note that there is no need to measure WTe and OsTe samples at liquid helium temperature, the liquid nitrogen temperature would be quite enough.

Some more complex compounds of Te are very interesting as well. For example, it was mentioned [4], that room temperature Moessbauer spectra of the 35.5 keV gamma resonance in ^{125}Te have become possible to observe using Mg_3TeO_6 matrix. The T-dependence of the f-factor in Mg_3TeO_6 host has shown that such matrix has rather high Debye temperature (~350K).

As a result, though we have already analyzed a number of Te compounds, which seem to be very useful for the experimental search of self-stimulation of long-lived nuclear isomers, some practical questions are still arising. Really, for some compounds, the techniques of their production are well-known and developed in detail so that they can likely be synthesized without serious difficulties, for other ones - additional tests should obviously be conducted. Unfortunately, the final conclusion is possible only after that as the f-factors of Te compounds are determined experimentally. It means once again that our Research Reactor has to be started.

IV. THE SIZE OF STIMULATED GAMMA-RAY EMISSION CROSS-SECTION

The following generally applicable formula for the cross-section of stimulated γ-ray emission was deduced [5]:

$$\sigma_{\gamma\gamma} = \frac{\lambda^2}{2\pi}\frac{\Gamma_\gamma}{\Gamma}, \qquad (2)$$

where λ is the wavelength of γ-ray radiation; Γ_γ and Γ are the radiative and total linewidths, respectively. It is obvious that, only when the transition is purely radiative and to the ground state,

the line-broadening factor would be equal to its maximum possible value of unity. When there are alternative modes of decay (either the internal conversion or any branching to different final states) or the lower state is not stable, the radiative width is to decrease. If there are no other contributors to the linewidth (neither Doppler broadening nor any type of inhomogeneous broadening), the lower state decay, internal conversion and branching were concluded [5] to be the primary reasons, which reduce the cross-section of stimulated γ-ray emission by broadening homogeneously the line and therefore decreasing the effective value of the linewidth factor.

Throughout the last decade, several publications appeared [6-18], in which authors have been disputing the general conclusion that the stimulated emission of recoilless γ-radiation, to say nothing of the stimulated emission gain, is extremely difficult to reach in the case of long-lived isomers. It was supposed that the formula for the stimulated emission cross-section (2) is correct only for Moessbauer transitions (transitions to the ground state of a nucleus), otherwise, for transitions between any excited states, the situation is utterly different: homogeneous line broading due to unstable lower state appears to be of no concern for such transitions (Fig. 2).

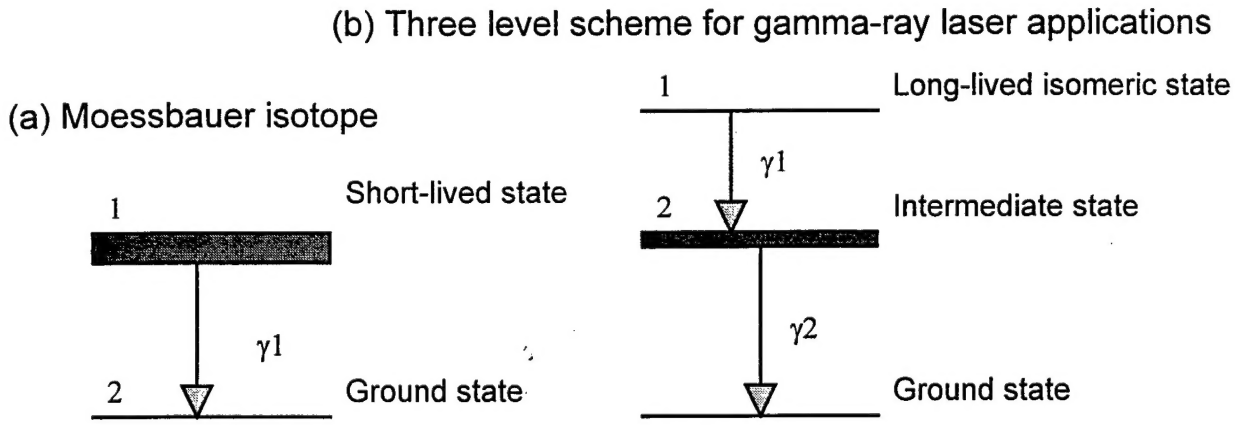

Fig. 2. Schematic representation of decay schemes for (a) Moessbauer isotopes and (b) long-lived nuclear isomers, which decay to the ground state through a short-lived intermediate nuclear level, rather than directly to the ground state as in the case of Moessbauer nuclei, and which could be useful for a γ-ray laser development.

So, for transitions to the excited state, (2) should be replaced by

$$\sigma_{\gamma\gamma} = \frac{\lambda^2}{2\pi}\frac{g_2}{g_1}, \qquad (3)$$

where g_1, g_2 - statistical weights of the upper and lower excited states, respectively. As a result, in the case of long-lived isomers, decaying to the ground state through a short-lived intermediate nuclear level, the size of the stimulated emission cross-section, estimated according to (3), turns out to be many orders of magnitude larger, than that expected from (2).

1. Semi-classical approach

To support the idea, for the three states of a nucleus in a cavity with walls at a uniform high temperature a derivation has been proposed [7], just like as Einstein did in his B-coefficient analysis [19,20]. Later on, the more correct analysis was presented [21] for such the system in thermodynamic equilibrium with thermal radiation, in particular, for the low-lying states of ^{125}Te (Fig. 3), which had been proposed to use for a γ-ray laser, just as the flow in the treatment [7] appeared to be identified. Really, the author [7] might be wrong, taking into account the fact that an intermediate level is unstable in a very strange manner: the intermediate state appears to be able to decay only spontaneously, whereas it can be neither dumped nor pumped by stimulation. At any rate, for the system in thermodynamic equilibrium with thermal radiation the spectral density of radiation under consideration has nothing to do with the spontaneous decay of the intermediate level, just as with stimulated transitions between the intermediate and ground states. To take into consideration all that correctly one must write the second equation, just as it was done in [21].

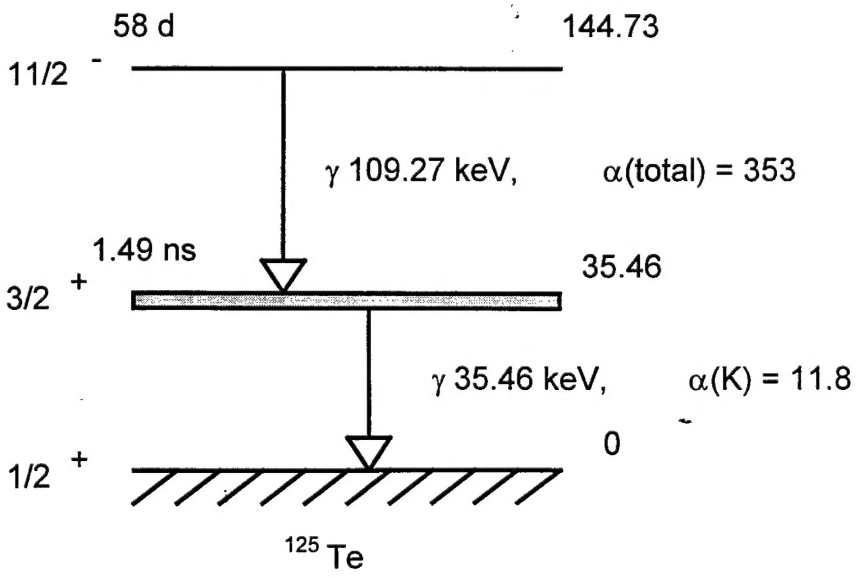

Fig. 3. The decay scheme for ^{125m}Te.

On the other hand, one can notice that Einstein considered a case of the radiation field with uniform frequency spectrum and some quantum system with sharply defined energy. In order to take into account the uncertainty principle it's quite enough to introduce the normalized line-shape function. At the same time, it was shown [22] that when the line width of radiation appears to be much wider than the radiative width of long-lived isomeric states, which is the case for the three-level-cascade nuclear system, the description turns out to be just the same. Thus, one may use the averaged spectral density of radiation. The radiative width corresponds to Einstein's A coefficient except for a factor $h/2\pi$, when energy units are used, so it must obviously lead to decreasing of the stimulated emission rate, because only a small fraction of the radiation field is in resonance with the nuclear system.

All the same, some doubts in the validity of such the consensus, that the stimulated emission of recoilless γ-radiation is extremely difficult to reach in the case of long-lived isomers, have still been remaining and that for several reasons.

First, there is the essential difference between the nuclear and electronic systems. In contrast with the electronic system, an excited nuclear state can decay not only through the radiative channel, but, at the energies below e^+e^- threshold, through the internal conversion as well. The nuclear systems can not, in principle, be in the equilibrium with electromagnetic field, since there is always an inelastic channel - internal conversion. As a result, for any real nuclear system, which may be proposed as a γ-ray laser, especially for a single-pass mirrorless device, which seems to be the most real in practice, the thermal equilibrium will never be reached. On one hand, because of the spontaneous decay by internal conversion, the equilibrium would obviously be only transient. On the other hand, the equilibrium requires definite time for it's establishing. Thus, it is doubtful that the assumption, that in the nuclear system the thermal equilibrium can be reached, should be an adequate approximation, as it was claimed in [21]. So, as Einstein's coefficients as their new relations, derived recently [7] for transitions between any two excited states of the quantum system, may be not valid for the nuclear system.

Secondly, the statement that in large population of similar nuclei, only which Einstein's treatment applies to, both kinds of transitions would be occurring concurrently between both pairs of states is also not so transparent in any real γ-ray laser material. Even the conclusion that the stimulated emission rate from the long-lived isomeric level has to be low, because the rate of spontaneous decay of the level is very low, appears to be not evident for a particular three-level-cascade nuclear system. All that was derived in the approximation that relative rates of the

spontaneous downward, stimulated upward and stimulated downward transitions must differ by just amount that maintains the Boltzmann distribution of populations in the bath of thermal radiation.

Third, there is common recognition that the rate of stimulated emission to a single mode must be equal to the product of the spontaneous decay rate to the mode and the number of photons in that mode [22]. The odd thing is that, according to the relation of Einstein's coefficients, the dependence includes the transition energy also, though one can note that such the relation between A and B coefficients is obviously the consequence of the frequency spectrum given by Planck's formula.

Fourth, for the nuclide ^{125m}Te the ratio of stimulated-emission coefficients turns out to be around 10^{-17}. So that in this or any other nuclide the stimulated emission between a very long-lived isomeric state and a very short-lived intermediate state is a minimal effect compared to the stimulated emission between the intermediate and ground states. Really, if the rate of spontaneous decay of the isomeric level is very low, then the stimulated emission rates to and from this level must be correspondingly low also. However, it is not obvious, why all said above should mean that the cross section for stimulated emission between the isomeric and intermediate states is small. The stimulated emission rates to and from the isomeric level could be low just because the stimulation under consideration occurs very and very infrequently. For example, if one takes the ratio of the stimulated-emission coefficient B and spontaneous emission coefficient A for the same transition, then for both transitions (between as the isomeric and intermediate states as the intermediate and ground states) these ratios are quite comparable (for the nuclide ^{125m}Te they are approximately 1:27), despite the extremely small ratio of the stimulated-emission coefficients. To be correct, since a γ-ray laser seems to be a single-pass device, one needs to consider the development of the burst of emission, at least, at equal conditions. So, the initial spectral density of radiation should not depend upon the transition under consideration - an electromagnetic wave of the resonant frequency with unit amplitude is injected into a extended pumped medium (essentially as by spontaneous emission).

And at last, if the storage and transfer processes prove to be feasible, for γ-ray lasers the maximum long-lived states, for which the Moessbaüer effect can still be assured to observe, are needed. It was really surprising that for such long-lived isomer as ^{109m}Ag ($T_{1/2} \cong 40$ s) some evidence of the resonant absorption has been reported [23-26]. Later the subject was re-examined theoretically [27] and it was found that, because of the extremely long lifetime, the interaction with lattice should lead to the homogeneous broadening, rather than inhomogeneous one, as it is

for the usual short-lived Moessbauer states. As a result, if the homogeneously broadened width exceeds the solid-state inhomogeneous width, then the Moessbauer effect can be observed in long-lived isomeric transitions. One ought to notice that such the conclusion is more than simply unexpected result as well. There is common practice to suppose that both homogeneous and inhomogeneous broadenings must lead to decreasing of linewidth factor, so that the resonant absorption cross-section appears to be only smaller. Really, in the case of the inhomogeneous broadening the resonant radiation interacts with only a small fraction of the nuclei. At the same time, when the homogeneous broadening appears, the radiation can interact with every nucleus, however, with much less probability. So, in both cases the result is to be the same. On the other hand, the idea itself seems to be very interesting. Really, to ensure the observation of the Moessbauer effect in long-lived isomeric transitions, it proves to be essential that the homogeneous broadening due to the interaction with lattice exceeds the solid-state-induced inhomogeneous broadening. So, why it is not the case that to ensure the observation of γ-ray stimulation in long-lived isomeric transitions, the homogeneous broadening due to the short-lived lower state would in the same manner help in overriding the solid-state inhomogeneous broadening.

2. Quantum mechanical description of the stimulation process as (γ, 2γ) reaction

Since the assumption of thermal equilibrium, used in the derivations [5,7,21], seems to be rather inadequate for nuclear systems, we have considered the stimulation process as (γ, 2γ)-reaction [28]. The S-matrix for stimulated emission can be written (h/2π = c =1) as [29]

$$S_{i\to f}^{(1)} = -e\int \overline{\psi}_2(x)\hat{A}^{*}(x)\psi_1(x)d^4x\sqrt{N_k} \quad , \tag{4}$$

where ψ_1 and ψ_2 are the initial and final intrinsic functions of the nucleus, respectively; N_k - the initial number of photons under consideration. Since the initial and final intrinsic functions of the nucleus and the vector potential of a monochromatic electromagnetic plane wave are

$$\psi_1(x) = e^{-i\varepsilon_1 t}\psi_1(\vec{r}) \quad , \tag{5}$$

$$\psi_2(x) = e^{-i\varepsilon_2 t}\psi_2(\vec{r}) \quad ; \tag{6}$$

$$A(x) = e^{-i\omega t}A(\vec{r}) \quad , \tag{7}$$

and exploiting the relation

$$\int e^{-i\varepsilon_1 t + i\varepsilon_2 t + i\omega t}\,dt = 2\pi\delta(\varepsilon_1-\varepsilon_2-\omega) \quad , \tag{8}$$

then the S-matrix for stimulated emission becomes

$$S^{(1)}_{i\to f} = -\,2\pi i\, U_{i\to f}\,\delta(\varepsilon_1-\varepsilon_2-\omega)\ , \tag{9}$$

where

$$U_{i\to f} = -ie\int \overline{\psi}_2(\vec{r})\hat{A}^*(\vec{r})\psi_1(\vec{r})d\vec{r}\ , \tag{10}$$

In the case, when the half-life of the excited level turns out to be definite, then the following replacements have to be done: $\varepsilon_1 \to \varepsilon_1 + i\pi/2$, $\varepsilon_2 \to \varepsilon_2 + i\pi/2$ and $\delta(\varepsilon_1-\varepsilon_2-\omega) \to$ Lorentzian function. In particular, for a photon with the impulse $\vec{k}$ and polarization $\vec{e}$

$$U_{i\to f} = -\frac{e}{\sqrt{2\omega}}\int \psi_2^*(\vec{r})\vec{\alpha}\,\vec{e}\,e^{i\vec{k}\vec{r}}\,\psi_1(\vec{r})d\vec{r}\ , \tag{11}$$

Making use of the relation

$$\delta^2(\varepsilon_1-\varepsilon_2-\omega) = \delta(\varepsilon_1-\varepsilon_2-\omega)\frac{1}{2\pi}\int_{-\infty}^{+\infty} e^{\,i(\varepsilon_1-\varepsilon_2-\omega)t}\,dt = \delta(\varepsilon_1-\varepsilon_2-\omega)\frac{1}{2\pi}T\ , \tag{12}$$

the probability per second for emitting a photon in the unit energy interval will be

$$W = \frac{|S|^2}{T} = \frac{4\pi^2|U|^2\delta^2}{T} = \frac{4\pi^2\delta|U^2|T}{2\pi T} = 2\pi\,|U|^2\,\delta(\varepsilon_1-\varepsilon_2-\omega)\,N_k\ , \tag{13}$$

The radiative transition rate, i.e. the radiative width of the transition 1→2 (see Fig. 2b), can be written as

$$\Gamma_\gamma(1\to 2) = \frac{1}{2I_1+1}\sum_{m_1,m_2,\nu}\int 2\pi\,|U|^2\,\delta(\varepsilon_1-\varepsilon_2-\omega)\frac{d^3k}{(2\pi)^3} =$$

$$= \frac{1}{2I_1+1}\sum_{m_1,m_2,\nu}\frac{1}{4\pi^2}\int k^2 dk\,d\Omega_k\,|U|^2\,\delta(\varepsilon_1-\varepsilon_2-\omega) =$$

$$= \frac{\omega^2}{4\pi^2(2I_1+1)}\int d\Omega_k\sum_{m_1,m_2,\nu}|U|^2, \tag{14}$$

where I_1 and m_1 are the spin and it's projection on the quantilization axis in the initial state of the nucleus, respectively; m_2 - spin projection on Z-axis in the final state of the nucleus; ν - polarization of the photon.

The cross-section for induced transitions may be estimated as the stimulation probability per unit flux of photons - W/(c/Ω) (for normalized volume Ω = 1 and c = 1). By averaging over the initial states and summing over the final states of the nucleus one can obtain

$$\sigma_{\gamma\gamma} = \sum_{m_1,m_2}\frac{1}{2I_1+1}[W/N_k] = \frac{1}{2I_1+1}\sum_{m_1,m_2}2\pi\,|U|^2\,\delta(\varepsilon_1-\varepsilon_2-\omega) =$$

$$= 2\pi\,\delta(\varepsilon_1-\varepsilon_2-\omega)\frac{1}{2I_1+1}\sum_{m_1,m_2}|U|^2\ , \tag{15}$$

Since the magnitude of the transition matrix element, summed over magnetic quantum numbers, does not depend upon both angles and photon polarization, then

$$\sigma_{\gamma\gamma} = 2\pi\,\delta(\varepsilon_1-\varepsilon_2-\omega)\,\frac{1}{2\cdot 4\,\pi\cdot(2I_1+1)}\sum_{\lambda,m_1,m_2}\mathrm{d}\Omega_k\,|\,U\,|^2 =$$

$$= 2\pi\,\delta(\varepsilon_1-\varepsilon_2-\omega)\,\frac{\pi}{\omega^2}\,\frac{\omega^2}{8\,\pi^2(2I_1+1)}\int \mathrm{d}\Omega_k\sum_{m_1,m_2,\lambda}|\,U\,|^2\quad , \tag{16}$$

Substituting (14) into (16), one can write

$$\sigma_{\gamma\gamma} = 2\pi\,\delta(\varepsilon_1-\varepsilon_2-\omega)\,\frac{\pi}{2\omega^2}\,\Gamma_\gamma(1\to 2)\quad , \tag{17}$$

Moreover, taking into consideration that [30]

$$\frac{1}{2\pi}\int_{-\infty}^{+\infty} e^{\,i\omega t-(\Gamma|t|/2)}\,dt = \frac{1}{2\pi}\int_{-\infty}^{0} e^{\,i\omega t+(\Gamma t/2)}\,dt + \frac{1}{2\pi}\int_{0}^{+\infty} e^{\,i\omega t-(\Gamma t/2)}\,dt = \frac{1}{2\pi}\quad , \tag{18}$$

$$\delta(\varepsilon_1-\varepsilon_2-\omega)\to\frac{1}{2\pi}\,\frac{\Gamma}{(\varepsilon_1-\varepsilon_2-\omega)^2+\frac{1}{4}\Gamma^2}\quad , \tag{19}$$

the cross-section for induced transitions becomes

$$\sigma_{\gamma\gamma} = \frac{\pi}{2\omega^2}\,\frac{\Gamma\cdot\Gamma_\gamma(1\to 2)}{(\varepsilon_1-\varepsilon_2-\omega)^2+\frac{1}{4}\Gamma^2}\quad , \tag{20}$$

So, substituting $\omega = \dfrac{2\pi}{\Lambda}$

$$\sigma_{\gamma\gamma} = \frac{\Lambda^2}{8\pi}\,\frac{\Gamma\cdot\Gamma_\gamma(1\to 2)}{(\varepsilon_1-\varepsilon_2-\omega)^2+\frac{1}{4}\Gamma^2}\quad , \tag{21}$$

If the induced radiation is at exact resonance with the transition ($\omega=\varepsilon_1-\varepsilon_2$), then

$$\sigma_{\gamma\gamma} = \frac{\lambda^2}{2\pi}\,\frac{\Gamma_\gamma}{\Gamma}\quad , \tag{22}$$

just as it was derived in [5].

As a result, by exploiting both S-matrix and line-shape factor for the stimulated transition to the excited state just the same, as for the spontaneous transition, we, unfortunately, have failed to find really strong theoretical arguments to support the newly derived formula for the cross-section of stimulated γ-ray emission. So, one may conclude that taking into account all the arguments mentioned above, the question about the size of stimulated γ-ray emission cross-section is still an open one and further research on the subject is clearly needed.

V. CONCLUSION

The question whether the stimulated decay of long-lived nuclear isomers is really possible or not is extremely important for as the γ-ray laser problem itself, as the whole fundamental science. If the stimulated emission of γ-rays can still be observed, then the prospects of a γ-ray laser is not so cloudy at all. Furthermore, if the stimulated emission cross-section turns out to be so large, as it was claimed more than decade ago (one could hardly even imagine such lucky case), there is no doubt that some prototype of a γ-ray laser is to be developed in the nearest future. So, it is a great pity that we did not managed to perform our experiments due only one, very simple, but very crucial technical problem - the pumping of our samples with reactor neutrons. At the same time, we'd like to hope that we shall be able to get a chance for the successful solution of the problem.

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